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MICROCOMPUTER CONTROL OF A HYDRAULIC POWER ELEMENT

by

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Microcomputer Control of a Hydraulic Power Element

by

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ABSTRACT

The Navy uses electrohydraulic servomechanisms throughout the fleet in the control of vehicles, weapons, and platforms. Better understanding of how these systems work will lead to ways of improving their performance, safety, and reliability. Microprocessor control allows the combining of various inputs and responses into the feedback control action of these systems in order to increase their performance. An attempt has been made to develop a "user friendly" microprocessor control system to be used to study the effects of frequency, load, pressure and flow on a typical hydraulic control system. Discussed in this thesis will be the effect of microprocessor control of electrohydraulic servomechanisms using a Macintosh computer.

THESIS DISCLAIMER

The reader is advised that the computer codes presented in this research have not been tested under all possible operating conditions or current operating systems for the Macintosh. Effort has been made to run the programs on the most current operating system available and to the best of the researchers ability in the time available, to ensure that the programs are free of computational and logical errors. Any use of these programs without user verification is at the risk of the user.

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I. INTRODUCTION

A. BACKGROUND

1. Servovalve Description

An electrohydraulic servovalve is a device that takes an electrical input (command signal) and positions a valve spool in order to control a hydraulic output. Typically the electric signal drives a simple torque motor or other electrical actuator which is either directly coupled to the valve spool or controls a flapper which indirectly controls the spool position by a pressure differential.

Servo systems of the past have been plagued with " . . . poor reliability, large size (heavy) and based on vacuum tube technology. They were sensitive to contamination and were costly to maintain" [Ref. 1:p. 1]. Improved systems are now available with increased reliability in electronic control components. There have also been significant advances in oil filtration techniques and higher immunity of hydraulic components to contamination. Improvements in electric and hydraulic segments of the servovalve have resulted in lower weight, higher spool driving forces and, in some valves, lower cost.

2. Application of Electrohydraulic (EHD) Servovalves

Electrohydraulic (EHD) servovalves were introduced in the Navy as one of the components that allowed the positioning and stabilization of gun mounts, radar antennas and missile launchers on board ships, thus allowing a more accurate fire control solution and weapon delivery. The Army also required stable platforms for their armored vehicle weapon systems.

Industrial uses include a variety of applications throughout manufacturing plants and the machine tool industry. For instance, in a plant that produces highly polished metal,

velocity servo systems are used to control a buffing machine. The servo drives a continuous sheet of metal through a buffing station where the special finish is produced. The material thickness varies as it passes through the buffing station. Uniformity and appearance depends upon the ability of the servo drive to accurately control the proper speed of the metal through the buffer. Another application is in the EHD velocity control of pinch-roll drive motors in a continuous billet casting machine. [Ref. 2:pp. 57-59, 141-143]

3. Advantages of EHD Servovalves

In servo systems the hydraulic fluid acts not only as a power transmission medium but as a lubricant as well. In many power systems, machine generated heat due to friction causes breakdown of lubricant and seizing of components such that cooling is required to extend component life. The hydraulic fluid in a servo system can be cooled in a sump or via an alternate convenient heat exchanger, thus extending component life.. Better cooling leads to smaller and lighter components. Merritt [Ref. 3:p. 1] indicates that modern hydraulic systems can be made in the 2 hp/lb range which makes them especially suitable for mobile and airborne equipment.

When compared to similar electrical systems, hydraulic actuators provide faster response (start/stop/speed reversals). Hydraulic actuators have large torque to inertia ratios. This results in good acceleration capabilities which make them advantageous in high-power, light weight applications. Hydraulic actuators are a convenient means for providing linear motion and they can operate under a wide variety of conditions without damage i.e. stalled, intermittent, reversing or continuous. They have higher stiffness, resulting in smaller drops in speed as loads are applied and better positional control with less error. [Ref. 3:pp. 1-2]

4. Control System Types

Control systems are the means by which servovalves can be used to obtain a high degree of accuracy in either the position or speed of an actuator and attached load. The type

of control varies depending on the type of system it is to be used with and the type of response desired. Control systems, used with servovalves, monitor an output (control variable) and compare it with the input (reference variable). The difference between the two signals (error) is used to reposition the valve in order to drive the system to a zero error in the presence of various disturbances. This error is often small in comparison to the input signal and needs amplification (gain) in order to increase the response of the system to the error. Care must be taken to ensure that the gains used do not drive the system to the point of instability.

a. Open Loop

In open loop systems an operator is often required to close the control loop and correct for disturbances. The system may have certain overriding controls to ensure that safety limits are not exceeded, such as maximum shaft torque, overspeed trips in velocity controlled systems, or maximum piston extension in position controlled systems. The operator link can be either a direct mechanical link or it can be a remote radio link so that the operator can be removed from a potentially dangerous environment. The key is that in open loop systems there must be an operator to make all the required adjustments to the system.

b. Closed Loop

In a closed loop system higher accuracy can be obtained by the continuous comparison and feedback of the error signal to the actuator. Less operator intervention is required to monitor the system. Adjustments are automatically made to the system to compensate for any disturbance which causes the output to differ from the input. This may be due to a desired change in the input, load variations or a change in the system operating conditions, such as oil temperature, causing the system parameters to change. Sensors used as signals in the feedback loop can include pressure transducers, flow meters, thermocouples, velocity transducers and position transducers.

More-sophisticated closed loop systems employ advanced techniques for signal processing. This usually involves the conversion of the commonly used analog control signals into digital form so that their values can be numerically manipulated. Some valves have been developed to operate directly from the resulting digital signals, others need to have the signal reconverted to an analog voltage.

5. Stability and Dynamic Response

Closed loop systems must be designed to avoid instabilities. If not carefully planned, a closed loop system can, in response to a disturbance, cause large error signals to be generated and dynamically amplified. This can continue until the oscillations in the system become so large as to cause component failure. Another possibility is to have the system stable yet have undesirable dynamic response. When properly designed, the closed loop system is stable providing prompt response and high following accuracy to a wide range of inputs.

6. Advantages Offered by Microprocessor Control

Henke [Ref. 4], discusses several advantages of microprocessor control. The microprocessor can be used as a pre-loop processor to perform keyboard reading and to process available information, or as a peripheral processor where the micro handles related information, ahead-of or after a conventional closed loop. Another advantage of microcomputer control of hydraulic servo systems is in the rapid collection of data. Once collected, the data may be numerically manipulated or monitored to check the trend in performance. Control adjustments, such as gain changes to improve performance, can then be made by the micro, if necessary. This is similar to another use called Adaptive Control where the the system can adjust itself to provide optimal, consistent control in response to identifiable system changes. Of particular use to the aircraft industry is "smart redundancy" where the micro is used to enhance reliability in multi-component systems. Another use is time-optimal control where, for example, the micro could determine the best switch point

and correct the switch point from cycle-to-cycle for force limited systems. These systems require minimum response time for any change in position. They apply full force for a portion of the actuator's stroke and then switch to adjust the force in the reverse direction, establishing the desired position in the minimum time.

Microcomputer control also allows the programming of a system ahead of time to allow different jobs to be performed by the system without operator control. Software could be designed for a system that can be easily modified for similar systems with the same processor. Different software packages allow even more flexibility for the system. For example preprogramming of micro controlled systems in rug weaving machines allow different patterns to be made without changing the equipment (i.e., cams). Other systems have been developed to control remotely operated coal mining equipment [Ref. 1:p. 1].

7. Related Work

A useful description of the role of microprocessors in closed loop electrohydraulic control systems has been given by Maskrey [Ref. 5]. Ashworth [Ref. 6], develops a mathematical model for the servo-system and discusses the problems of sampling frequency in micro-controlled systems. Chenoweth and Slaugh [Ref. 7], discuss "using microprocessor-based actuation controllers communicating with aircraft-control computers over digital data buses to control and redundancy manage the operation of one or more control-surface actuators." Burleigh and El-Ibiary [Ref. 8:p. 55], discuss the attainment of improved system performance and accuracy through the use of microprocessors in fluid power controls. More specifically, they discuss solid-state, pulse-width-modulating control of a variable volume pump and their development of an "Electronic Enhancer Controller" designed specifically for electrohydraulic control systems. Lin and Chen [Ref. 9], discuss their development and construction of an eight-bit single-chip microcomputer to control a hydraulic motor. Numerically controlled machine applications are discussed in Sosonkin's and Malyuga's article [Ref. 10]. This work describes the development of a

microcomputer-based control system with no electronic analog instruments and only one pulsed photo-electric sensor with position feedback for position and speed control.

B. OBJECTIVES

The primary objective of this thesis work has been to set-up a system where follow-on thesis students may learn more about microcomputer control of fluid power. This should allow students involved in the fluid power course to use microprocessor control for instructional labs. In addition, achievement of the primary objective will allow continual thesis research in the general area of microprocessor control. A variety of lab set-ups should be available for study of translational as well as rotational servomechanisms. The software used should be easy to learn and have the capability to allow a variety of programming languages to suit research needs. Hardware requirements include provisions for sufficient memory and storage capability to store programs used and data obtained from the system. Specifically the design criteria for the system is that it be

- Micro based
- Use an electrohydraulic motor as a power element
- Involve closed-loop speed control
- Have no more than 5% error in the servo loop which has only proportional control action (minimum system).

C. APPROACH

The first step in the approach to developing a working system was to analyze the conventional analog servoamplifier with the hydraulic system in order to develop a model. A linearity check of the operating range was required to ensure that linear approximations may be used. Linear approximations were to be used in modeling the servovalve in order to simplify the analysis, when within the operating range. Frequency response tests of the

system under various loads was necessary in order to estimate the characteristics for the hydraulic portion of the system. The results of this experiment led to an approximation of the natural frequency of the system, as well as the bandwidth and other required modelling characteristics.

In order to validate the model, an analysis of the model's response to step inputs was performed. With the model complete, i.e. the analog controller fully implemented and characterized, a similar system was developed using the microcomputer in place of the analog servoamplifier the conventional analog controller was translated into a digital system.

With the sampling interval determined from the frequency response tests, the digital system was designed. The microcomputer/ADC combination needed to be analyzed to determine if it could respond fast enough to control the system. In other words, we needed to determine the fastest system change to which the micro system could respond. With the microcomputer/ADC response known, then the computer code was written to control the system digitally. Once the code was written, all interfacing between the microcomputer/ADC and the hydraulic portion of the loop could be addressed.

D. EQUIPMENT ON HAND

An attempt was made to use on-hand equipment as much as possible. As more was learned about the system, more equipment was brought in to enhance the individual lab/experiment.

The hydraulic supply system used was a Vickers 1500 psi system. The primary additional hydraulic components used consisted of a 5 gpm servovalve and a hydraulic motor. Inertia load devices were designed and fabricated for testing both rotary and translational fluid power systems. The analog servoamplifier for the set-up is a Vickers multi-channel analog servoamplifier with installable modules for various controls.

The microcomputer selected for investigation was the 512K Macintosh (Mac). The decision was based on the familiarity of the Macintosh to the researcher. The corresponding analog-to-digital convertor (ADC) used for the Mac is a product from GW Instruments called MacADIOS. It comes with its own software and serial interface to the Mac. Among other things the software allows waveform graphing, generation and manipulation.

II. ANALOG SYSTEM

A. SYSTEM DESCRIPTION

With the analog servoamplifier connected to a servovalve on first a piston and then a motor, several experiments were run to verify and learn about the system's operation: The general layout is as shown in Fig. 1 below.

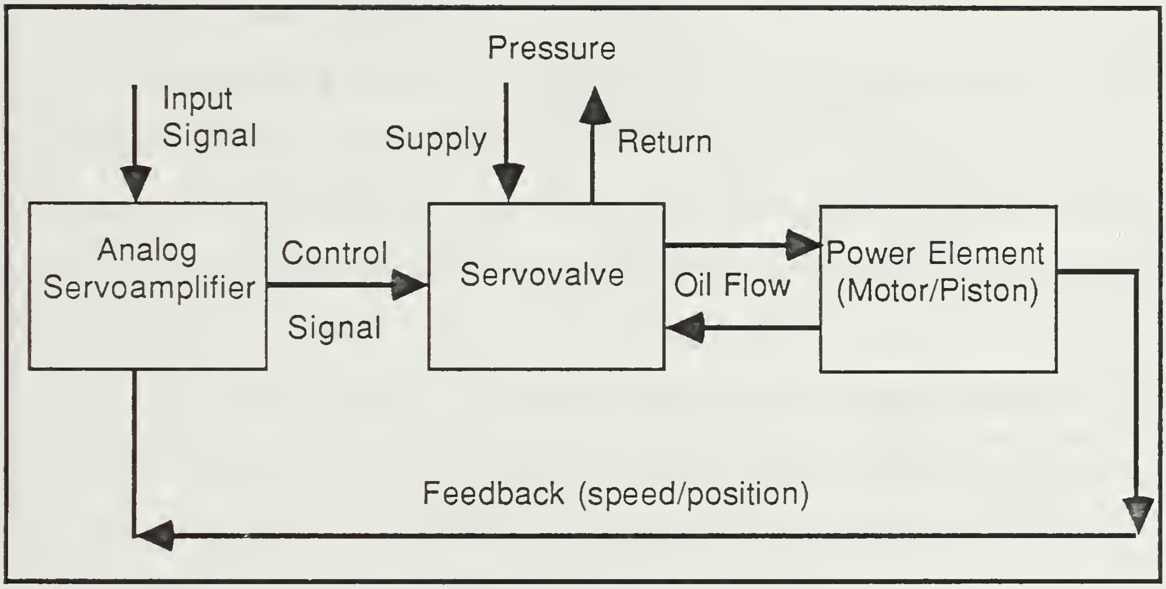

Figure 1. Functional block diagram of the electrohydraulic servo mechanism.

The instruction manual that came with the analog servoamplifier laid out both position control and speed control experiments. After correcting several wiring problems internal to the analog servoamplifier, the lab experiments were run. Performing these labs gave valuable experience in learning to set the proper gain, bias, dither, limiter and ratio settings internal to the analog servoamplifier.

A simplified circuit diagram of the servoamplifier is shown in Fig. 2. Inputs to the servoamplifier are usually supplied to terminals four or five unless balancing is required by means of the variable resistance available through terminals eight and nine. This is useful when the range of the feedback signal is not of the same magnitude as that of the the input signal, as is with the case of the tachometer output used for velocity feedback whose output is 45V/1000 rpm and the input or command signal is +/- 12 volts for the entire operating range.

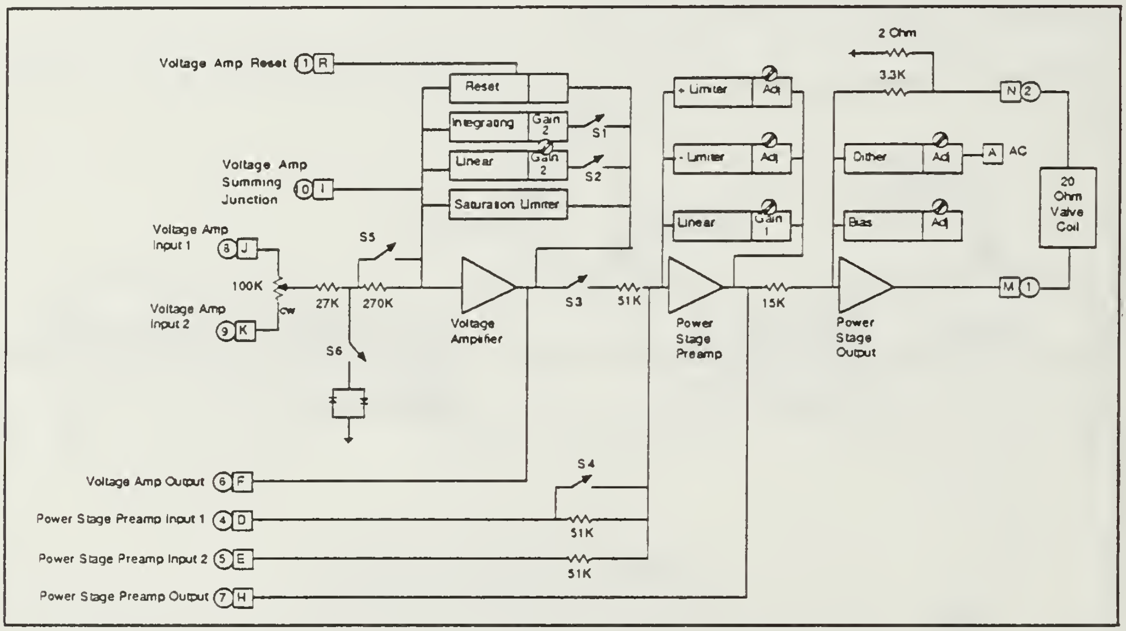

Figure 2. Analog servoamplifier

Input through terminals eight and nine allows the use of the voltage amplifier to provide proportional plus integral control action with reset. Desired control action is obtained through appropriate settings of the function switches shown in Fig. 2. The gain settings determine how much the input signal is amplified prior to being sent to the servovalve. The power stage preamp gain setting determines the amplification of the signal going to the servovalve (volts to milliamps), while the voltage amplifier gain controls the amplification

of the input from terminals eight and nine. The bias setting of the power amplifier controls the zero reference of the amplifier. It is adjusted such that with no input to the servoamplifier no current flows in the servovalve coils. The limiters, one for positive and one for negative voltages, prevent exceeding the maximum allowed current through the servovalve. Additional potentiometers (not shown in Fig. 2) are available for control of the reference input voltage to the amplifier.

B. STANDARD TESTS AND RESULTS

1. Linearity Check Of The Operating Range

After performing the preliminary tests suggested by the manufacturer, an open-loop linearity check of the motor speed versus input voltage was performed. A range of +/- 1000 rpm was chosen as one that would reflect a wide range of speed control and one that could be readily controlled within the limits of the system. The check was performed with 600 psi bench pressure set at 0 rpm, and this setting was not readjusted throughout the check. The tachometer voltage, processed through a signal conditioner and voltage divider, was used to determine shaft speed. The gain of motor speed in response to input voltage was found to be constant at 0.72 rpm/mv, within the precision of available instrumentation. The data obtained from this test are found in App. A.

2. System Frequency Response

Frequency response tests were performed using a signal generator for input and a strip chart recorder to measure the the servovalve/motor response from the tachometer. The amplitudes of the response as well as the amplitude of the input were recorded for comparison.

It is important to keep the amplitude of the input signal both as small as possible, yet large enough to see a response, and constant for the series of runs to be made. Merritt [Ref. 3:pp. 141-142], shows how changing the amplitude of the input can change the

damping coefficient. In tests where only the effect of different inertia loads are of interest, changing the amplitude would lead to misleading results. Further, if the amplitude is not kept small one risks leaving the linear portion of the valve operating characteristics. The larger the signal amplitude the further one is from a true linear response.

All frequency response tests were done open-loop to determine the bandwidth of the servovalve/motor combination under various load conditions. The results of the frequency response tests are given in App. A. The no-load results indicate a hydraulic natural frequency of 150 rad/sec or 24 Hz and a bandwidth of 300 rad/sec or 48 Hz, with bandwidth defined by the input frequency producing a 3-db attenuation in output amplitude. Following this test, a shaft was connected to the motor and then a sequence of increasing inertia loads in the form of steel disks were applied. The frequency response data was recorded and examined to verify that the natural frequency and bandwidth decreased as the load increased.

III. THE MICROPROCESSOR CONTROLLED SYSTEM

A. MAC/MACADIOS SYSTEM.

1. General

In order to make the connection between an analog system and a digital system, a digital-to-analog convertor is inserted between the micro and the conventional servo system as shown in Fig. 3. The equipment used is discussed and then two means of using the micro for control are demonstrated, first as a pre-loop processor and then as a processor in the closed loop.

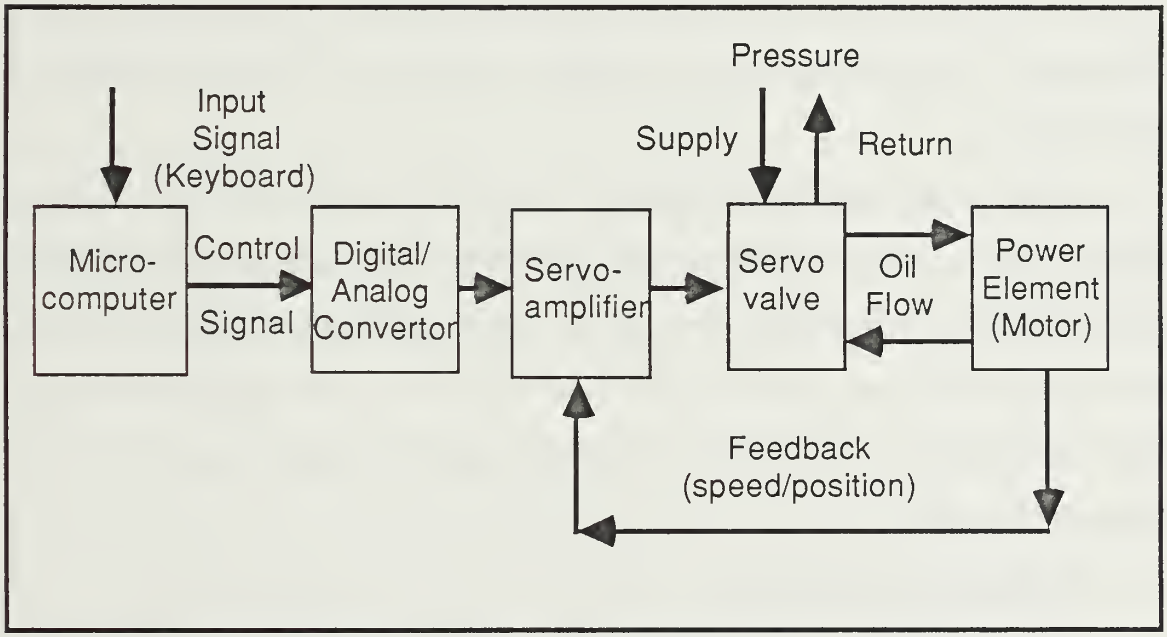

Figure 3. Functional block diagram of the electrohydraulic servo mechanism with the micro and digital-to-analog convertor.

2. Micro

The microcomputer used was an Apple Macintosh 512K upgraded to an Macintosh 512K Enhanced (E). It has 512 kilobytes (K) of memory, 128K of ROM, and an internal 800K double-sided disk drive that uses the 3.5 inch disks. An external 800K double-sided disk drive was used for data storage when required.

The main reason for using the Mac was prior familiarity with this system on the part of the investigator. However, the fact that it has a relatively inexpensive "third party" analog-to-digital convertor which used and followed the Mac interface, was also a strong consideration. The graphic capabilities of the Mac made it easy to look-at and manipulate the data generated. In addition, the ease of use, i.e., click and point type of interface, reduces the amount of time training other users. Another advantage is that the Mac can be attached to a wide variety of relatively inexpensive peripherals -- there are ample printers, laser printers, mass storage devices (hard disks) available to suit most data taking and analysis needs.

The primary drawback of the Mac is the lack of a wide variety of engineering oriented software. Although Microsoft has made FORTRAN-77 for the Mac few if any associated applications have been developed. Of primary importance to this work would be control oriented algorithms and optimization routines that could be integrated into the servo system control task. Another drawback is the fact that it lacks a math co-processor to speed up data manipulation.

3. Analog-to-Digital Convertor

The MacADIOS is the analog-to-digital/digital-to-analog convertor for the Macintosh, designed as a data acquisition system. The actual hardware unit used is from GW Instruments and called a Model 411 Hardware Unit. It comes with its own software compatible with the Macintosh operating system. Although the hardware unit has four 12-bit analog voltage outputs with a +/- 10 volt range and eight 12-bit analog voltage inputs

with a +/- 10 volt range, only a single input and single output channel was used in this work.

The software supplied with the MacADIOS that was primarily used in this work was the portion called the MacADIOS Manager (MM) and the library of BASIC routines to allow the MacADIOS to be controlled from Microsoft BASIC. The Monitor Window is one portion under the MM. The Monitor Window allows the Mac/MacADIOS system to emulate an eight channel digital voltmeter as well as send voltages through the four analog output channels. For the purposes of this work, the Monitor Window was most valuable in the day-to-day work with the servo system.

The sample time of the MacADIOS varies depending on the BASIC call used. The minimum time between samples is obtained by means of the HSAIN (high-speed analog in) function-call which will take as many samples as indicated in the call syntax, 48 microseconds apart, on any one channel. Two other high-speed sample rates are available at a 96 microsecond sample rate and a 192 microsecond sample rate. Both calls apply to sampling from one channel only. In order to sample from more than one channel, the lower speed calls must be used. The AINX (analog in) function-call samples from any or all of the 8 analog input channels at a 172 Hz rate or 5.81 milliseconds per sample. [Ref. 13:pp. 4-52 - 4-55]

The actual code used to program the Mac was Interpreted Microsoft BASIC. Here function-calls supplied with the MacADIOS software allowed the control of the output of the DAC and the recording of the input to the ADC. While working with the system, the MacADIOS Manager software was used prior to coding any programs, thus simulating portions of what the eventual code would do. This saved a great deal of time in that millivolt signals could be readily sent as an input to the system and the response of the motor monitored all on the same screen.

The primary advantage to this set-up was the compactness of the equipment involved, reducing the necessity for many wires to be strung between equipment components. In addition the multifunctional capability provides greater flexibility in how the signal is recorded, presented and analyzed.

The primary drawback of the equipment is the sample rate for a single sample. Although it is possible to sample a given channel quite rapidly, the call itself, in BASIC, takes a minimum amount of time to execute. This minimum time is on the order of five milliseconds. This limits the ability to rapidly take and manipulate data, and then send more data out. This would be critical when trying to alter the signal sent to the servo system in the middle of a transient, particularly with more than one input.

Another drawback is the programming language used to operate the MacADIOS. Basic is not a relatively fast language but, due to the relative ease of use, it proved to be effective as a first approach while learning the system. There is code supplied to control the MacADIOS in MANX C. C is, relatively speaking, a much faster language than BASIC and may aid in speeding-up the control algorithms.

B. THE MICROCOMPUTER AS A PRELOOP PROCESSOR

1. Discussion

Using the microcomputer as a preloop processor allows a program to determine the proper input to activate the servo system. The servo system responds to the output of the microcomputer as a closed-loop dynamic system. The advantage here is that a conventional, well known technology is employed in designing the servo system and digital sampling is not involved. The difference between this system and the conventional analog system is that instead of the conventional analog power supply and potentiometers being adjusted by human control, the microcomputer, ADC and associated software, make the adjustments based on some preset criteria prescribed in the software program.

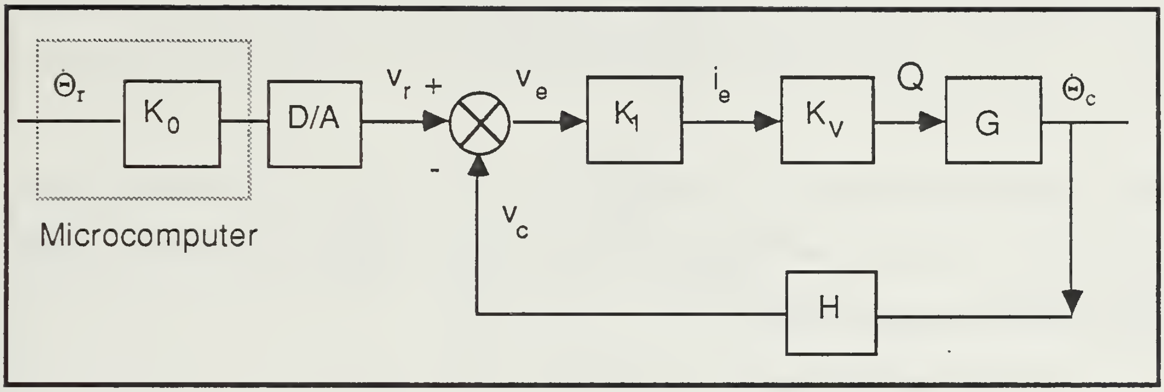

Figure 4. Microcomputer as a preloop processor.

2. Analysis

Referring to the block diagram in Fig. 4, an analysis was done to find the overall transfer function between the motor shaft speed ($\dot{\Theta}_c$) and the analog voltage out of the micro/DAC (v_r). The following symbols appearing in Fig. 4 are defined as follows;

$\dot{\Theta}_r$ = the digital representation of desired (reference) shaft speed as an integer variable, rpm.

K_0 = conversion between the digital variable for shaft speed and voltage out of the DAC, mv/rpm.

v_r = reference voltage out of the DAC, mv.

v_e = error voltage to the servoamplifier, mv.

v_c = command voltage corresponding to actual shaft speed, mv.

K_1 = servoamplifier gain. This is adjustable through gain 1 (Fig. 2) from 0.11 to 1.52 ma/mv. Experimental measurements determined the actual minimum value for K_1 to be 0.105 ma/mv.

i_e = current from the servoamplifier to the servovalve coils, ma.

K_v = servovalve gain. This value was found from the relationship

$$K_v = \frac{Q}{i} = 0.00352\sqrt{P_s - P_L}$$

The constant value 0.00352 was found experimentally and has units of [in^3/sec-ma-psi$^{1/2}$]. Using 600 psi supply pressure and assuming $P_L = 0$ for the maximum value of K_v, a value 0.0862 in^3/sec-ma is determined.

G = plant transfer function, rpm/(in^3/sec).

$\dot{\Theta}_c$ = actual shaft speed, rpm.

H = tachometer/signal conditioner gain. This value was measured and an average value of 2.19 mv/rpm was determined.

The closed loop transfer function is

$$\frac{\dot{\Theta}_c}{\dot{\Theta}_r K_0} = \frac{K_1 K_v G}{1 + K_1 K_v G H}$$

The plant G, or motor and load, taken from Merritt [Ref. 3:p. 259], is

$$G = \frac{\frac{1}{D_m}}{\frac{s^2}{\omega_h^2} + \frac{2\delta_h}{\omega_h}s + 1}$$

Where ω_h is the hydraulic undamped natural frequency in rad/sec, δ_h is the hydraulic damping ratio and is dimensionless, and D_m is the motor displacement in in^3/(sec-rpm).

D_m is given as 0.0114 in^3/(sec-rpm) in the technical manual, but experimental results show that the value for the motor in use was 0.0116 in^3/rad. Substituting gives,

$$\frac{\dot{\Theta}_c}{\dot{\Theta}_r K_0} = \frac{\dfrac{K_1 K_v}{D_m}}{\dfrac{s^2}{\omega_h^2} + \dfrac{2\delta_h}{\omega_h}s + (1 + \dfrac{K_1 K_v}{D_m}H)}$$

Applying the final value theorem to determine the steady-state response for a step input one obtains,

$$\left[\frac{\dot{\Theta}_c}{\dot{\Theta}_r K_0}\right]_{SS} = \frac{\dfrac{K_1 K_v}{D_m}}{1 + \dfrac{K_1 K_v}{D_m}H}$$

Of interest is the steady-state response. With the values listed above, the steady-state response is 0.29 [rpm/mv].

$$\left[\frac{\dot{\Theta}_c}{\dot{\Theta}_r K_0}\right]_{SS} = 0.29$$

The steady-state system error is, referring to Fig. 4,

$$\left[\frac{v_e}{v_r}\right]_{ss} = 1 - \frac{H}{K_0}\left[\frac{\dot{\Theta}_c}{\dot{\Theta}_r}\right]_{ss} = 0.37 \text{ mv/mv}$$

In order to obtain a unity response between the desired and actual speed, K_0 may be set at the inverse of the response (1/0.29) $\{[\text{rpm/mv}]\}^{-1} = 3.4$ [mv/rpm]. This is scaling or calibrating the input voltage to obtain the desired speed out.

3. Response

The above model was coded and run under DSL in order to obtain an idea of how the actual system should respond to a series of step inputs. The code is given in App. B. The results for a series of 100 mv step inputs were recorded and then compared to the actual response.

Having learned how the system should respond, a BASIC program was written to control the system and was tested in the lab. A series of step inputs were performed and the results tabulated. The code and a summary of these results are given in App. B. The agreement between the two, the model and the actual system, were within the uncertainty of the gains in the model. Fig. 5 compares the predicted and actual results. Here the desired speed is the value of the step input to the system, both for the DSL program as well as for the actual test in the lab. The actual shaft speeds are steady-state values observed in the actual test, and the predicted speed values are those returned from the DSL program.

The model, i.e., the DSL predicted values, are very close to the desired speed values as seen by the nearly one-to-one relationship in Fig. 5. However, the actual shaft speed falls off at higher desired speeds. This is a result of the design being a minimum system, i.e., having only proportional control, and the actual system not behaving linearly throughout the entire region. In particular, the gain K_v is suspect due to its dependency on the square root of the difference between the supply pressure and the load pressure drop. In the actual test the supply pressure decreases and the load pressure increases as the speed increases. These pressure changes result in K_v becoming smaller at the higher speeds with a corresponding decrease in feed-forward gain.

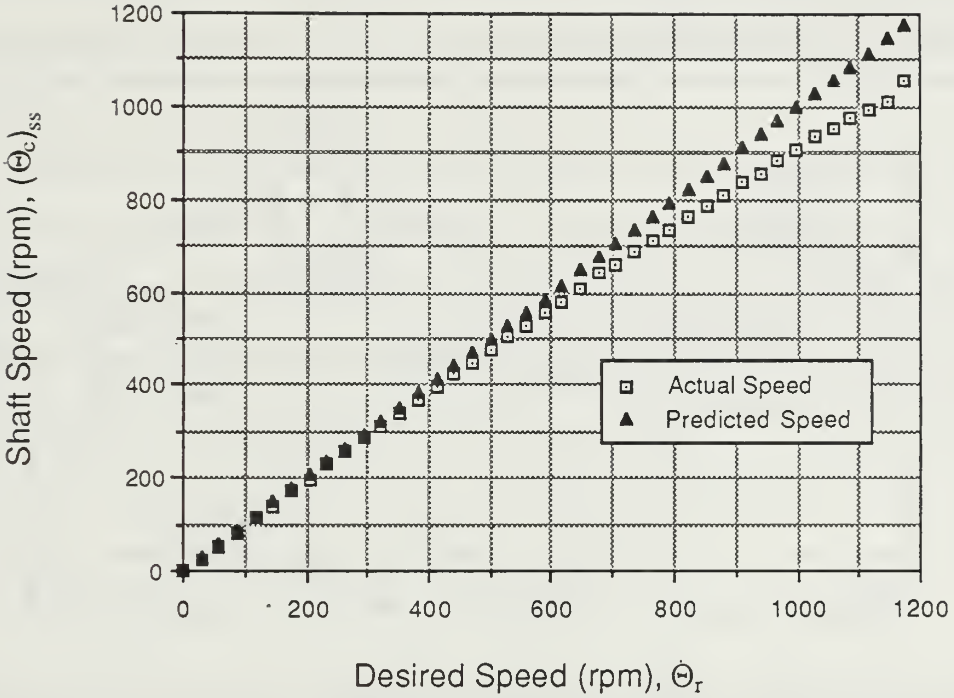

Figure 5. Steady-state results of tests of closed-loop speed control using the microcomputer as a preloop processor.

C. THE IN-LOOP MICRO-CONTROLLED EHD SYSTEM

1. Discussion

The microcomputer controlled set-up, shown in Fig. 6, is not all that different from the analog set-up. The additional requirements are digital processing and the DAC/ADC. In addition, the reference input signal is generated from a keyboard input and associated software. The feedback signal from the tachometer is stepped-down through a voltage divider and fed through the ADC into the microcomputer in order to generate the control signal. The control signal is, in turn, converted to analog form for input to the servovalve.

In order to incorporate the microcomputer into the system a signal amplifier was needed to boost the output from the DAC. The power amplifier built into the

servoamplifier's network was used to perform this function in order to reduce the amount of additional equipment needed.

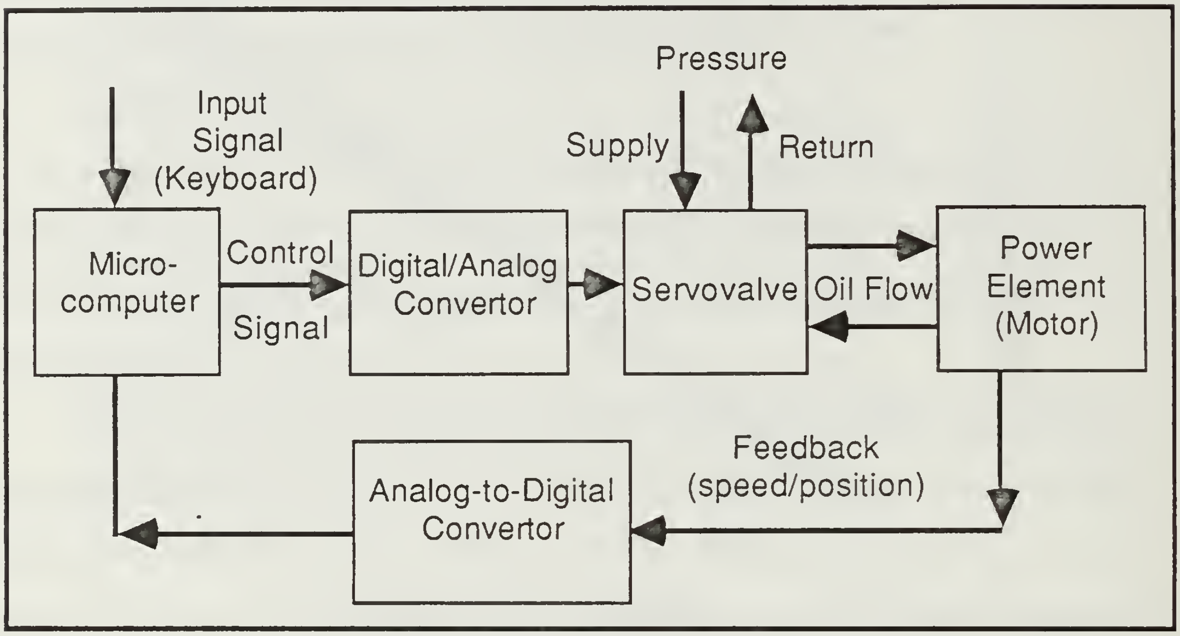

Figure 6. Block diagram of microcomputer control of the EHD servomechanism.

2. <u>Sampling</u>

The sampling rate of the microprocessor for digital data acquisition must be fast enough to reproduce the sampled analog data with sufficient accuracy. Theoretically, if the sampled signal has a major frequency content up to ω_1 then the minimum sampling rate, ω_s, required is

$$\omega_s \geq 2\omega_1 \ .$$

This avoids aliasing, the condition where two signals give the same quantized values from the ADC and can't be distinguished. In practice, one prefers sampling frequencies ten times greater than the maximum expected signal frequency [Ref. 11:p. 101]. Referring to the unloaded frequency response test of the motor, the bandwidth of the system was approximately 48 Hz. This should reflect the maximum frequency that the microprocessor

will be required to sample. Following the 'ten times the signal frequency' guideline, gives a required sample frequency of 480 Hz or a time-between-samples of approximately 2.0 milliseconds.

Sampling time for control purposes is related to system response requirements. A sampling trade off check is just one part of the control design process. That is, in order to keep up with and control the system, the control algorithm must execute sufficiently fast enough to process the machine code as well as complete the sampling process at a frequency well beyond the bandwidth of the system to be controlled. The efficient use of programming code must be applied as well as the use of a programming language which is fast enough to meet the timing requirements. This work used interpreted BASIC, a relatively slow language, in the check of the trade-off between code execution rate and bandwidth considerations. Any language or compiled version of BASIC that was faster than what was used here would improve system response.

3. Analysis

With the knowledge that the system was responding as predicted in the model for the preloop processor, a closed loop experiment was developed with the microcomputer in the loop. The system block diagram is shown in Fig. 7.

Here the summing junction has been moved to a point inside the microcomputer. This requires that feedback signals be converted through the ADC to a digital representation of speed. The summing point compares digital representations of speed, rather than analog voltages as in the preloop processor. The digital representation of the error signal is converted to a voltage signal for the DAC to send to the servovalve.

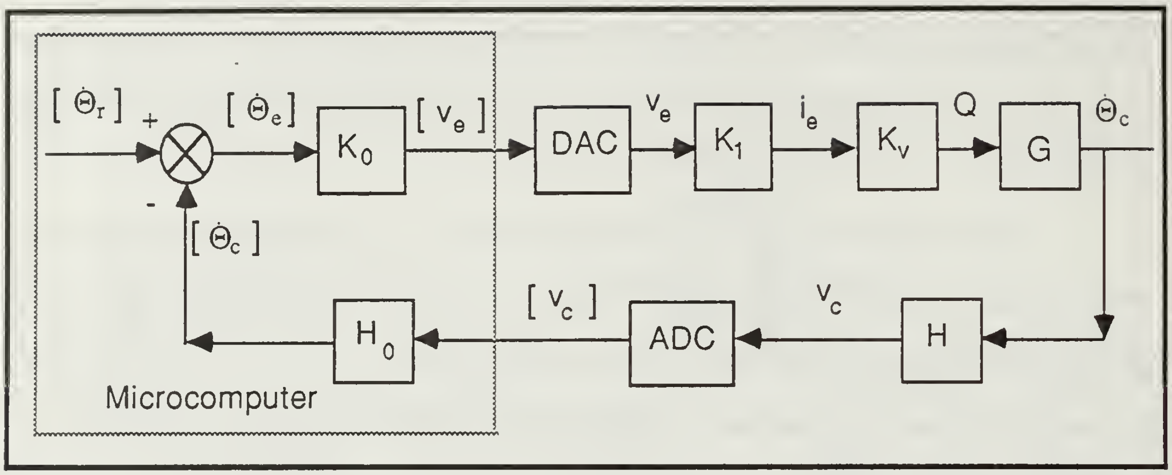

Figure 7. Closed loop control with the microcomputer in the closed loop.

Referring to the block diagram shown in Fig. 7, an analysis was done for the ideal case of an infinitely fast sample and control computational rate, to find the overall transfer function between the motor shaft speed ($\dot{\Theta}_c$) and the desired speed entered from the keyboard as input to the microcomputer [$\dot{\Theta}_r$]. The following symbols appearing in Fig. 7 are defined as follows,

[$\dot{\Theta}_r$] = the digital representation of the desired (reference) shaft speed as an integer variable, [rpm].

[$\dot{\Theta}_c$] = the digital representation of actual (control) shaft speed, [rpm].

[$\dot{\Theta}_e$] = the digital representation of the speed error, [rpm].

K_0 = conversion between the digital variable for speed error and digital voltage entering the DAC, [mv/rpm].

[v_e] = the digital representation of the error voltage to the servoamplifier, [mv].

H = tachometer/signal conditioner gain. In these tests the effect of the signal conditioner was determined to be an average of 4.08 mv/rpm.

[v_c] = the digital representation of the voltage corresponding to actual shaft speed, [mv].

H_0 = conversion between the digital representation of the voltage from the tachometer to the digital representation of the shaft speed, 0.245 [rpm/mv]. Other symbols appearing in Fig. 7 are identical in meaning to those defined in Fig. 4.

The closed loop transfer function is,

$$\frac{\dot{\Theta}_c}{[\dot{\Theta}_r]} = \frac{K_o K_1 K_v G}{1 + K_o K_1 K_v G H_0 H}$$

The plant G, or motor and load, is the same as for the preloop processor,

$$G = \frac{\frac{1}{D_m}}{\frac{s^2}{\omega_h^2} + \frac{2\delta_h}{\omega_h}s + 1}$$

Substituting gives,

$$\frac{\dot{\Theta}_c}{[\dot{\Theta}_r]} = \frac{\frac{K_o K_1 K_v}{D_m}}{\frac{s^2}{\omega_h^2} + \frac{2\delta_h}{\omega_h}s + (1 + \frac{K_o K_1 K_v H_o H}{D_m})}$$

In order to simplify the equations, assign K as an overall gain,

$$K = \frac{K_o K_1 K_v H_o H}{D_m}$$

Substituting gives,

$$\frac{\dot{\Theta}_c}{[\dot{\Theta}_r]} \quad \frac{\dfrac{1}{H_0 H}\,\dfrac{K}{1+K}}{\dfrac{s^2}{\omega_h^2(1+K)} + \dfrac{2\delta_h}{\omega_h(1+K)}s + 1}$$

Applying the final value theorem and looking at the response for a step input one obtains,

$$\left[\frac{\dot{\Theta}_c}{[\dot{\Theta}_r]}\right]_{ss} = \frac{1}{H_0 H}\,\frac{K}{1+K}$$

4. Steady-state Response

Again, the interest is the steady-state response. The desired response is,

$$\left[\frac{\dot{\Theta}_c}{[\dot{\Theta}_r]}\right] = 0.95$$

Substituting in the known values one finds the steady-state response equal to,

$$\left[\frac{\dot{\Theta}_c}{[\dot{\Theta}_r]}\right] = \frac{K_0}{1.285 + K_0}$$

5. Results

K_0 was determined based upon the desired steady-state error criteria of 5% and its value was found to be 24.4. It should be noted, however, that this value of K_0 reduces the

effective closed-loop damping constant by a factor of $(1 + K)^{1/2}$ equal to 4.47, with attendant reduction in system stability. A DSL program was written to model the system neglecting the actual sample rate, and the system behavior was analyzed. The simulation code is given in App. C.

With the results of the DSL program known, a program in BASIC was written to control the closed loop system. The code and flow chart are given in App. C. The actual system was more unstable than the DSL program predicted and, in fact, any K_0 over 1.1 mv/rpm resulted in widely unstable oscillations. A value of 1.0 mv/rpm was used for comparison with the DSL results in order to validate the program. A typical system response is shown in Fig. 8, where motor speed is shown as a function of the sample number. The sample number correlates to roughly 0.1 seconds, as the BASIC program used did not allow recording time below a one second increment, the exact value could not be determined.

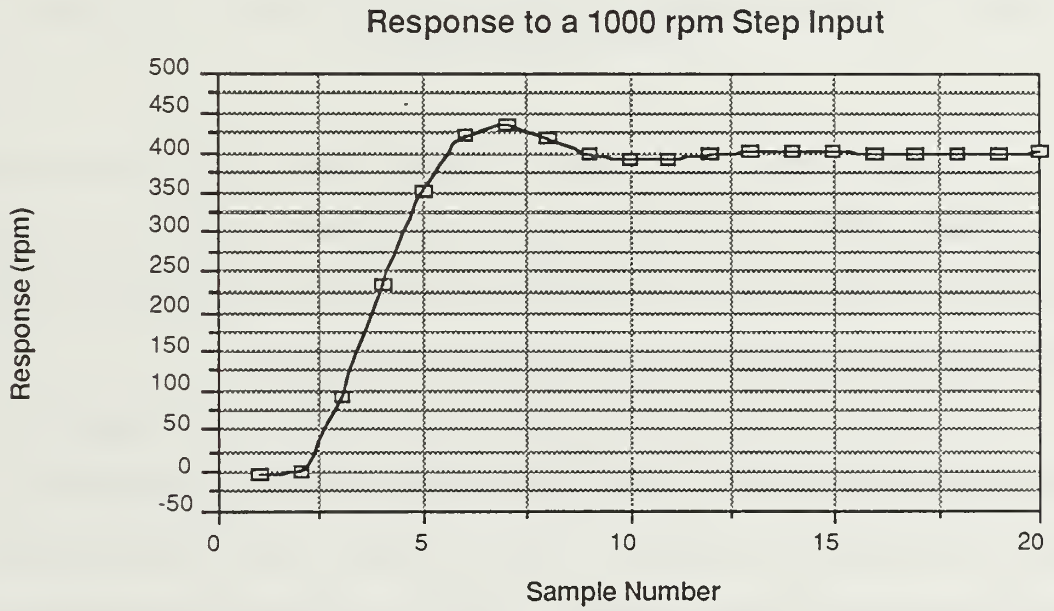

Figure 8. Typical system response to a step input (microprocessor control).

The DSL program predicted a steady-state response gain of 0.44. So for a 100 rpm input, the predicted response would be 44 rpm. The actual test of the system revealed a ratio of steady-state response to reference input closer to 0.42, as shown in Fig 9.

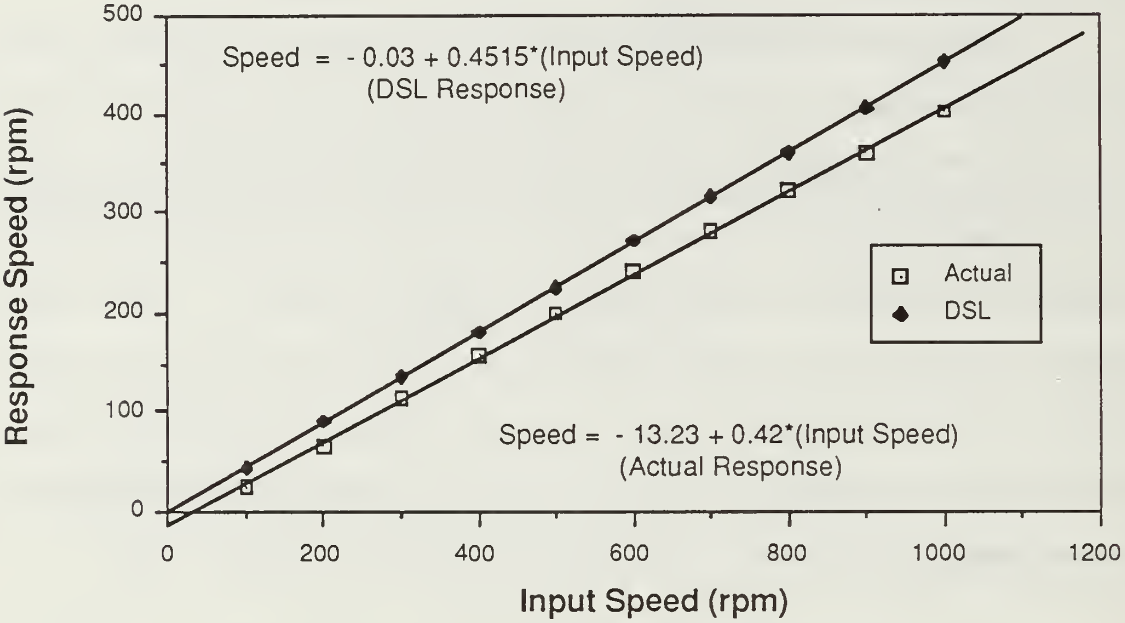

Figure 9. Actual and predicted motor steady-state speed response to a step input (microprocessor control).

As the size of the input increased the difference between the predicted and the actual response increased. As in the preloop processor application, this is expected due to the nature of the using only proportional control in the system, as well as the model program assuming no change in the supply pressure or load pressure.

The response of the system is much lower than that actually desired. This indicates that the gain is too low, but as K_0 was increased the system became unstable. As explained in Merritt [Ref. 3:p. 260], " . . . electrohydraulic velocity control loops must always be compensated to achieve stability". Therefore before the gain can be increased some means of decreasing the system bandwidth is required such that the crossover frequency becomes less than the natural frequency of the hydraulic element. This may be

in the form of an integrator in the loop ahead of the servovalve to constantly sum the errors and apply the result as a compensator. With the loop properly compensated the gain can be increased until the response meets the desired input. Because of time constraints, compensation was not attempted. These results do show, however, that microprocessor control is effective within the stability limits inherent in the uncompensated system.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSION

Microcomputer control of EHD servovalves is possible with the Macintosh computer and the MacADIOS analog-to-digital convertor. The system set-up allows for further work in a variety of related areas. Some of these areas are discussed in the recommendations. The micro was shown to be able to act as a preloop processor, and as a viable controller for slow response operation in the closed loop. The design criteria not met was that of the allowed steady-state error. It was found that the minimum system would not support a sufficiently high enough gain to allow reducing the stead-state error to five percent while maintaining a stable system without provision for error compensation. Further work in this area is required. System response is limited by control sampling rate and further work with more rapid microprocessing arrangements is needed.

B. RECOMMENDATIONS

1. Loop Analysis

Investigate timing effects. This could be done with the Z transform of the continuous time plant model. The simulation will be required to anticipate how the actual system will behave at discrete times, then simulated tests could be implemented on the real system. One would expect better response with the system controlled by a timer in which the corrections to the output signal would be based on the more accurate discretized system model.

2. Closed Loop Step Response (Motor)

Whereas the above recommendation would be an attempt to improve the loop as a whole, another step would be to look at the rise time, maximum overshoot, steady-state error, the natural frequency and damping coefficients of the system to better understand these different performance criteria and system characteristics. These studies would include different input levels as well as various models of the system. The results should show the points where the linear assumptions break down or where new coefficients should be used to reflect a new linear operating range. These sets of data could then be used in future programs that would be used to cover an entire operating range. With a more exact model for the closed loop, an optimal gain schedule could be programmed for a wide range of operating conditions.

3. Closed-Loop Frequency Response (Motor)

Closed loop frequency response tests would be used to determine the natural frequency of a given system. As inertia loads are added one should be able to analyze how the natural frequency of the system changes. One must be careful not to change the amplitude of the input signal as this results in masking the true operation of the system when comparing it to other loads. The process can then be repeated with different loading conditions.

4. Piston Response

Since a large variety of hydraulic systems involve the positioning of loads using a piston arrangement, the above analysis should be repeated using a piston actuator.

5. Cross Port (Inlet/Outlet) Leakage

Once more is known about the damping of the system, the load and other system characteristics can be held constant and the damping of the servovalve can be adjusted using the crossport leakage path. A study of these effects may show an optimal amount of crossport leakage in order to improve system performance.

6. Position Control With A Rack And Pinion

As with the piston type experiments and modeling, position feedback can be obtained through the use of a motor and a rack and pinion arrangement. It is easier to visualize the steady state error when position control is used as compared to speed control.

7. Determine The Bulk Modulus

Much is yet to be determined concerning the actual physical constants of the system. Work in this area could help determine the true bulk modulus of the system. This could be done with a low friction piston arrangement by displacing the actuator at a given pressure and measuring the displacement. With the input signal held constant, displacement changes in response to pressure variations would be measured. These two changes along with the initial volume of the cylinder, would allow calculation of the bulk modulus, where the bulk modulus is defined as;

$$\frac{1}{\beta_e} = \frac{-\Delta V_t}{V_t \Delta P}$$

8. Optimal Control

Optimal control may be able to be set-up on the Mac with a Fortran compiler and source code from a program like CSMP or DSL. One would have to work out the communication between the Fortran and the A/D convertor.

9. State Feedback

In the work to date on this system only one control variable was used in the feedback. A hydraulic system has other variables that effect the way it works. Utilizing state feedback one could bring in other control variables, as well as speed or position, such as load pressure drop and temperature. Then this information could be integrated into the

optimal controller to chose the proper gains for the system over a range of operating conditions.

10. Hydraulic System Enhancements

Critical to the continuity of any work on the system is the ability to continue to work with the system in the event of a component malfunction. An entire backup set-up should be purchased to avoid long delays in working with the system should a component failure occur.

Adding an accumulator to the hydraulic power supply system could aid in providing a more steady supply pressure when loaded. The accumulator may also allow running two set-ups at once without large fluctuations in supply pressure.

Adding a regulated heating and cooling system to the sump that allowed maintaining a constant oil temperature throughout an experiment would be advantageous. This would require a cooling system as well as a calibrated thermostat to be added to the present system. With this installed, temperature effects on the system could be studied.

11. Programming

One of the weakest areas in the present software for the system is the use of interpreted BASIC instead of a compiled version. A compiled version became available at the end of the work and should be employed in any further work where speed is needed. BASIC is also relatively slow. This could be improved by using C, possibly Fortran, or machine language. By speeding up the control algorithm higher frequency response may be obtained, faster sampling and correction can be achieved with a resultant improvement in system performance.

12. Interfacing Equipment

When reworking the set-up, care should be exercised in the type of cables used. Shielded cables should be used and, if possible, a single master cable from the MacADIOS 37 pin D connector should be used. In addition, care in matching the output impedances of

the sensing devices to one another, in order to minimize interferences, will prevent having to reanalyze the system for different equipment configurations.

13. Types Of Control

With the loop fully modeled and understood, one could incorporate different types of control in the closed loop. Modeling and experimenting with different types of control action such as integral, proportional, differential or combinations of each, may lead to better response to a given input. These could be combined in the velocity feedback loop to provide the compensation needed to improve the steady-state response.

APPENDIX A

BASELINE SYSTEM TESTS

1. SYSTEM LINEARITY CHECK

A motor speed response test was performed in order to observe how linear the response was to the input voltage over the operating range. The test was done open loop by inputting a series of millivolt step inputs into the system and recording the steady-state response. Fig. A1 shows the responses with an initial supply pressure of 600 psi with an input of 0 mv. Although a quadratic approximation is more accurate, it is close to being linear over a majority of the operating range. The small offset at zero input volts appears as a result of a slight bias within the servovalve itself.

Approximation for Motor Speed = $-20.99 + 0.72*(\text{Input mv}) + 3.06\text{x}10^{-6}*(\text{Input mv})^2$

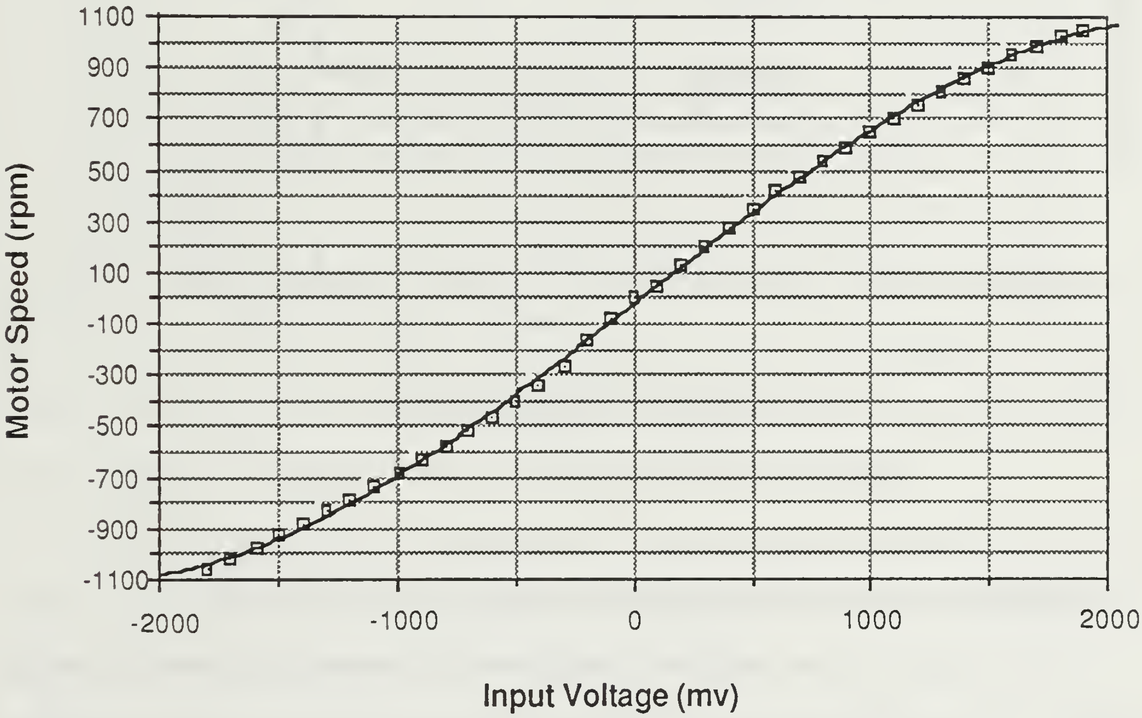

Figure A-1. Open Loop Motor Response to Supply Voltage

2. UNLOADED MOTOR FREQUENCY RESPONSE

This data was used to determine the bandwidth and natural frequency of the system with the motor unloaded. Using Ogata's [Ref. 12:p. 439] definition for the bandwidth as applied to an open loop system, Fig. A2 shows the bandwidth which equals the cutoff frequency (ω_c) defined as the frequency at the 3db down point. The cutoff frequency is approximately 300 rad/sec or 48 Hz. The natural frequency (ω_n) is found at the frequency corresponding to the resonance peak. In this case the natural frequency is approximately 150 rad/sec or 24 Hz.

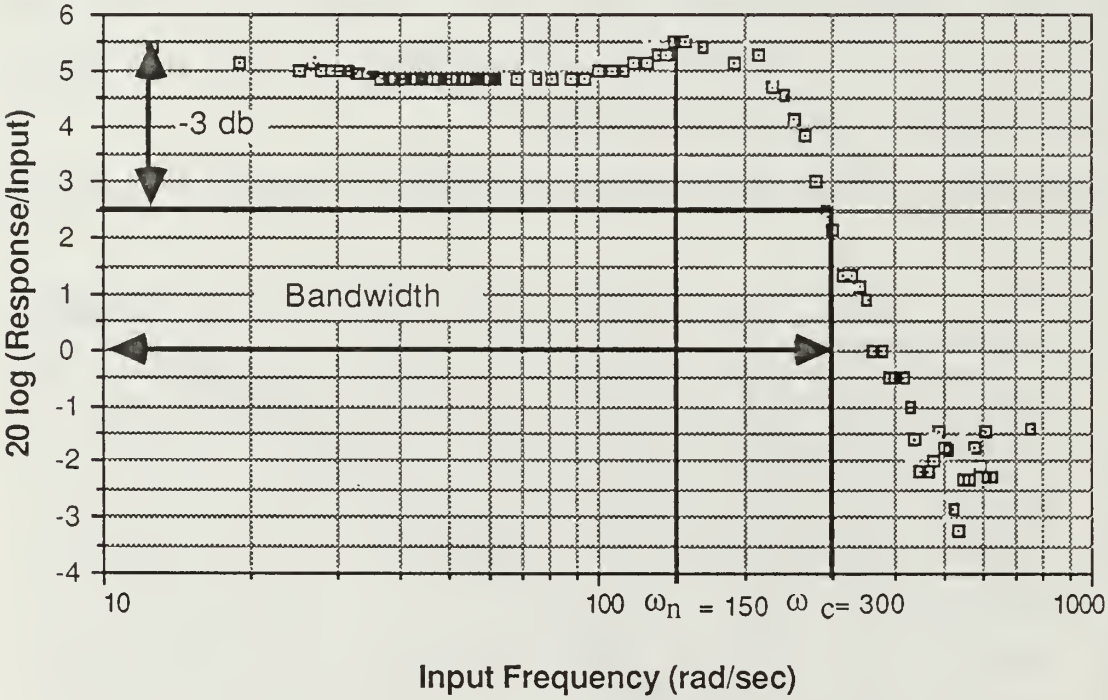

Figure A2. Unloaded motor frequency response.

3. SYSTEM FREQUENCY RESPONSE WITH THE MOTOR LOADED

A shaft was used to allow additional inertia loads to be added to the motor. Loading the motor with the load shaft alone gives the response seen in Fig. A3, and corresponding

changes in the system natural frequency and bandwidth. The natural frequency has dropped to 90 rad/sec or 14 Hz and the bandwidth has been reduced to 150 rad/sec or 24 Hz.

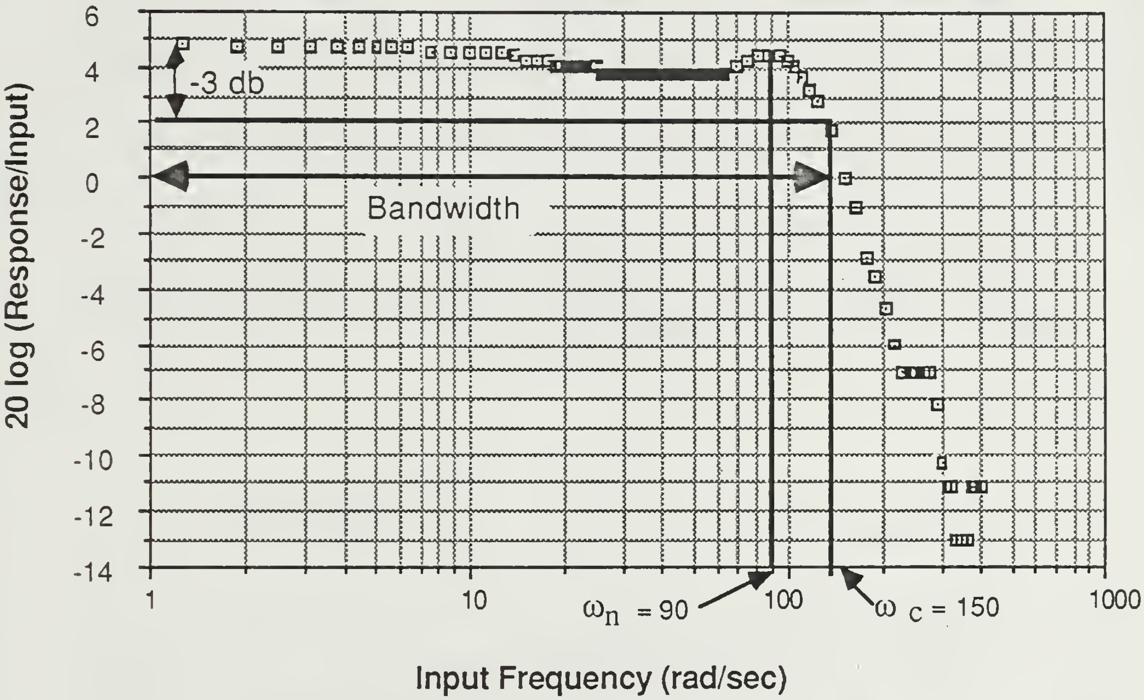

Figure A3. Frequency response of motor with shaft.

Fig. A4 shows the results of the frequency response test with additional inertia load. Here two disks have been added to the motor shaft. The natural frequency of the system has been reduced to 60 rad/sec or approximately 9 Hz, and the bandwidth has been reduced to 90 rad/sec or 14 Hz.

Fig. A5 shows the system response when four disks have been added to the motor shaft. The natural frequency of the system has been further reduced to 30 rad/sec or less, and the bandwidth has been reduced to 70 rad/sec or 11 Hz.

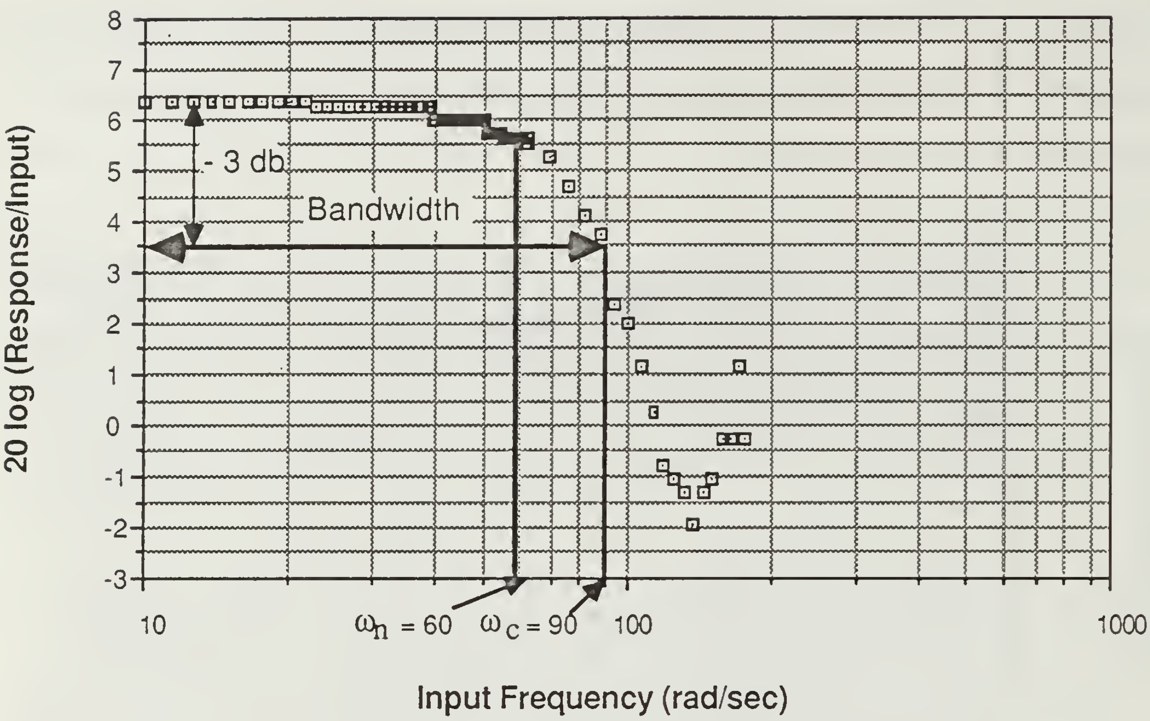

Figure A4. Frequency response of motor with 2 disks.

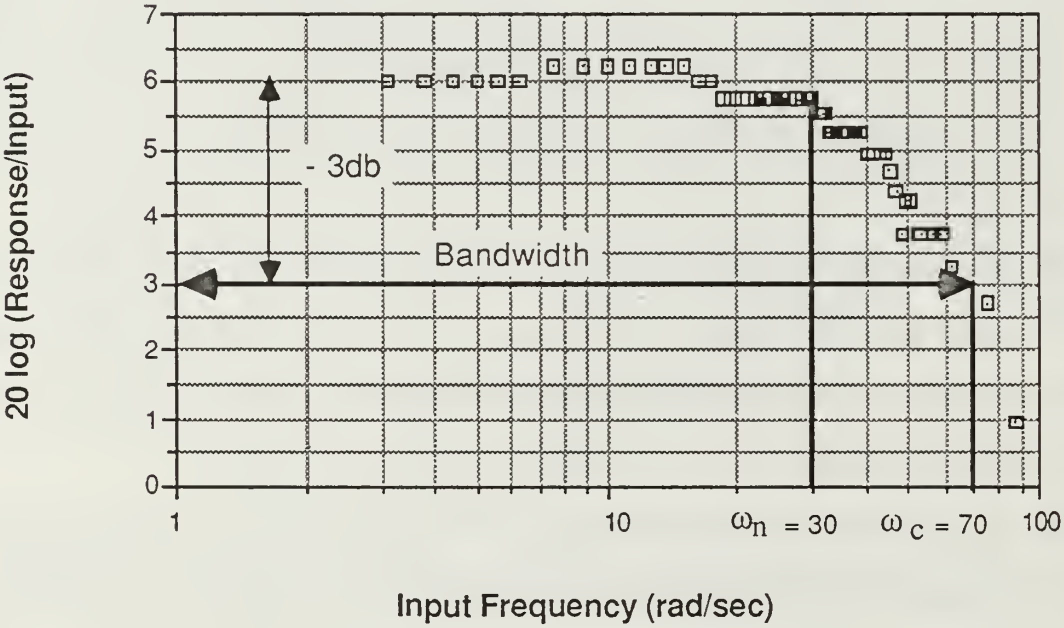

Figure A5. Frequency response of motor with 4 disks.

APPENDIX B

PRELOOP PROGRAM LISTINGS

1. DSL LISTING OF PRELOOP PROCESSOR SIMULATION

The following listing is the program used to model the preloop processor, written in DSL. The program makes a series of 100 rpm step inputs to the system and prints out the response.

```
*      PRELOOP PROCESSOR SIMULATION
*      THIS PROGRAM SIMULATES THE MICRO AS A PRELOOP PROCESSOR
*       FOR A SERIES OF STEP INPUTS.
*
TITLE PRELOOP PROCESSOR
*
*      VARIABLE DEFINITIONS
*      A = DUMMY VARIABLE
*      A*TETAC = COMMAND OR ACTUAL SHAFT SPEED RAD/SEC
*      DM = MOTOR DISPLACEMENT CUBIC INCHES/RAD
*      H = TACHOMETER AND SIGNAL CONDITIONER GAIN MV/(RAD/SEC)
*      K1 = SERVOAMPLIFIER GAIN MA/MV
*      KV = VALVE COEFFICIENT (CUBIC INCHES/SEC)/MILLIAMP
*      MAG = AMPLITUDE OF STEP INPUT
*      P1,P2 = DUMMY VARIABLES
*      TETACO = SHAFT SPEED IN RPM
*      VC = FEEDBACK VOLTAGE MV.
*      VE = ERROR VOLTAGE.MV
*      VR = REFERENCE OR INPUT VOLTAGE MV
*      WH = HYDRAULIC NATURAL FREQUENCY RAD/SEC
*      ZETA = HYDRAULIC DAMPING COEFFICIENT
*
PARAM WH=170.,ZETA=0.5,KV=0.0862,DM=0.11,H=20.91
PARAM MAG = 0.
INITIAL
      MAG=MAG + 100.
      K1=0.11
      P1 = ZETA/SQRT((1+(K1*KV*H)/DM))
      P2 = WH*SQRT((1+(K1*KV*H)/DM))
      A=(WH**2)*K1*KV/DM
DERIVATIVE
      VR = MAG*STEP(0.0)
      TETAC = CMPXPL(0.,0.,P1,P2,VR)
DYNAMIC
      TETACO = A*TETAC*9.55
```

```
      VC = TETAC*H*A
      VE = VR - VC
TERMINAL
      IF (MAG.EQ.4000.) CALL ENDJOB
      CALL RERUN
CONTROL FINTIM=1
SAVE .1,TETACO,VR,VC,VE
GRAPH(DE=SPRINT) TIME,TETACO,VR,VC,VE
PRINT .1,TETACO,VR,VC,VE
END
STOP
```

2. MICROSOFT BASIC PROGRAM FOR THE PRELOOP PROCESSOR

The following listing is the code used to control the preloop processor system. It takes a desired speed, in rpm, from the keyboard as input. The steady-state result is read from the dynamometer display in rpm and manually recorded.

```
REM    Preloop Processor program modified 11/3
REM
REM    This is a program to cause the MacAdios to output a
REM    desired voltage from channel 0 given an Speed in rpm
REM    when asked.

LIBRARY "Macadios calls"   ' loads index of library routines
CALL mainit  ' initialize the modem port to accept signals

start:                               ' label for start of program
REM    print out the heading on the screen
     PRINT    "Input the desired speed in RPM."
     INPUT DesSpd
     PRINT    "Desired speed is ",DesSpd  '
     GOTO A2D

done:                              'label for end of program
     CALL closelib ("Macadios calls")  ' close the library
END

A2D:                            'label for A-to-D conversion
REM    compute correct output voltage for desired speed =
Inpmv%(mv)
     vmv = DesSpd/.2937
     Inpmv% = CINT(vmv)
     CALL aout(Inpmv%,0,0,0)  'send Inpmv% to channel 0 of
MacADIOS
GOTO start
```

3. PRELOOP SUMMARY

Table B1 is the summary of the results from the DSL simulation and the actual tests. The desired speed is the step input to both the DSL simulation as well as the BASIC program of the actual test. The input voltage is the resulting voltage sent from the MacADIOS as a result of the BASIC program. The predicted and actual speeds are the results from the DSL simulation and the actual test, respectively.

TABLE B1. PRELOOP DATA

Desired Speed (rpm)	Input Voltage (mv)	Predicted Speed From DSL (rpm)	Actual Shaft Speed (rpm)
0.0	0	0	0
29.369	100	29.374	21
58.737	200	58.75	52
88.106	300	88.125	81
117.474	400	117.5	112
146.843	500	146.87	140
176.211	600	176.25	170
205.580	700	205.62	198
234.949	800	235.00	228
264.317	900	264.37	256
293.686	1000	293.75	285
323.054	1100	323.12	312
352.423	1200	352.50	339
381.791	1300	381.87	365
411.160	1400	411.25	394
440.529	1500	440.62	425
469.897	1600	470.00	450
499.266	1700	499.37	476
528.634	1800	528.75	504
558.003	1900	558.12	529
587.372	2000	587.5	559
616.740	2100	616.89	582
646.109	2200	646.27	608
675.477	2300	675.64	644
704.846	2400	704.99	660
734.214	2500	734.37	689
763.583	2600	763.74	711
792.952	2700	793.12	737

TABLE B1. PRELOOP DATA (cont.)

Desired Speed (rpm)	Input Voltage (mv)	Predicted Speed From DSL (rpm)	Actual Shaft Speed (rpm)
822.320	2800	822.49	761
851.689	2900	851.87	786
881.057	3000	881.24	808
910.426	3100	910.62	836
939.794	3200	939.99	858
969.163	3300	969.37	883
998.532	3400	998.74	906
1027.900	3500	1028.1	938
1057.269	3600	1057.5	952
1086.637	3700	1086.9	974
1116.006	3800	1116.2	994
1145.374	3900	1145.6	1013
1174.743	4000	1175.0	1058

APPENDIX C

INLOOP PROGRAM LISTINGS

1. DSL LISTING OF THE INLOOP PROCESSOR SIMULATION

The following program is the program used to model the inloop processor, written in DSL. The program uses a K_0 of 1.0 and an initial step input of 100 rpm then reruns, increasing the size of the input in 100 rpm increments up to 1000 rpm.

```
TITLE CLOSED LOOP PROCESSOR KO = 1.0 MV/RPM
PARAM
K1=0.11,KV=0.0862,H=38.46,HO=0.026,DM=0.11,WH=170.,ZETA=.5,MA
G=0.
INITIAL
        MAG = MAG +100
        KO = 1.0
        K = KO*0.8228
        P1 = ZETA/SQRT(1+K)
        P2 = WH*SQRT(1+K)
        SS = K/((1+K)*HO*H)
DERIVATIVE
        THETAR = MAG*STEP(0.0)
        THETA = CMPXPL(0.,0.,P1,P2,THETAR)
DYNAMIC
        THETAC = THETA*SS*(P2**2)
        NDIGTL = THETAC*H*HO
        THETAE = THETAR - NDIGTL
TERMINAL
        IF (MAG.EQ.1000) CALL END JOB
        CALL RERUN
CONTROL FINTIM = .1
SAVE 0.001, THETAR,NDIGTL,THETAE,THETAC
PRINT .001, THETAR, NDIGTL, THETAE, THETAC, SS
END
STOP
```

2. BASIC LISTING FOR THE INLOOP PROCESSOR

The following is the MS BASIC code written for the inloop processor. The program will ask for a desired speed to be entered at the keyboard. It will record the speed from the

output of the tachometer and write it to a text file on disk. When the desired time has elapsed the program is stopped manually. To make another run first rename the output file, stop the motor with a zero rpm input and then run the program again keying in the new desired speed.

```
REM    Thesis program 13, Closed Loop Speed Control
REM    This program is designed to move the summing point
REM    inside the micro.  This is a program to cause the
REM    MacAdios to output a desired voltage from channel 0
REM    given an RPM when asked and then sample the tachometer
REM    speed/voltage and compare the desired rpm and the
REM    actual rpm.  If they don't match, change the input
REM    voltage.


LIBRARY "Macadios calls"   ' loads index of library routines
CALL mainit  ' initialize the port to accept A/D signals

REM Initialize array and other variables

   DIM Tachmv%(10),deltim(1000), shftspd(1000), sigerr(1000)
      erin% = 0  '  error parameter
      DesSpd = 0      '  desired speed
      spderr = 0     '  speed error
      Inpmv% = 0     ' Input to power amp in mv, an integer
      Tachmv% = 0     'output from tachometer/signal
      tachspd = 0' converted tachometer speed
      Ko = 1! ' converts rpm to mv
      i = 0
      deltim(0) = 0

   OPEN "Closed loop data" FOR OUTPUT AS #1
start:                                '  Begin the program
   PRINT "Input the desired speed in RPM between +/-1000."
   PRINT "A value outside this range will exit the program."
   PRINT #1,"Input the desired speed between +/-1000 rpm."
   PRINT #1,"A value outside this range will exit program."
   INPUT DesSpd
   PRINT "Desired speed is ",DesSpd, "rpm"  ' display speed
   PRINT #1,    "Desired speed is ",DesSpd, "rpm"  '
   PRINT #1, "time            shaft speed       error speed"

   IF DesSpd <=1000 AND  DesSpd >= -1000 THEN GOTO Sample

REM if outside the +/- 1000 rpm limit exit the program
   CALL closelib ("Macadios calls")  ' close the library
   PRINT "Speed outside limits of Program, program stopped."
```

```
   PRINT #1, "Speed outside limits, program stopped."
END

Sample:
   REM sample the tachometer
   CALL
ainx(0,0,1,VARPTR(erin%),VARPTR(Tachmv%(0)),0,0,0,0,0,0,0)
   REM     compute the corresponding shaft speed
   tachspd = -.5056 + .2452 *Tachmv%(0)
   spderr = DesSpd - tachspd
   deltim(i) = TIMER - deltim(0)
   shftspd(i) = tachspd
   sigerr(i) = spderr
   PRINT #1 deltim(i);shftspd(i);sigerr(i)
   i = i+1
REM   compute correct output voltage for desired speed =
Inpmv% (mv)
   vmv = spderr*Ko
   Inpmv% = CINT(vmv)
   CALL aout(Inpmv%,0,0,0)  ' send Inpmv% to channel 0 of
MacADIOS
GOTO Sample
```

3. PROGRAM FLOW CHART

Fig. A6 illustrates the control for the BASIC program.

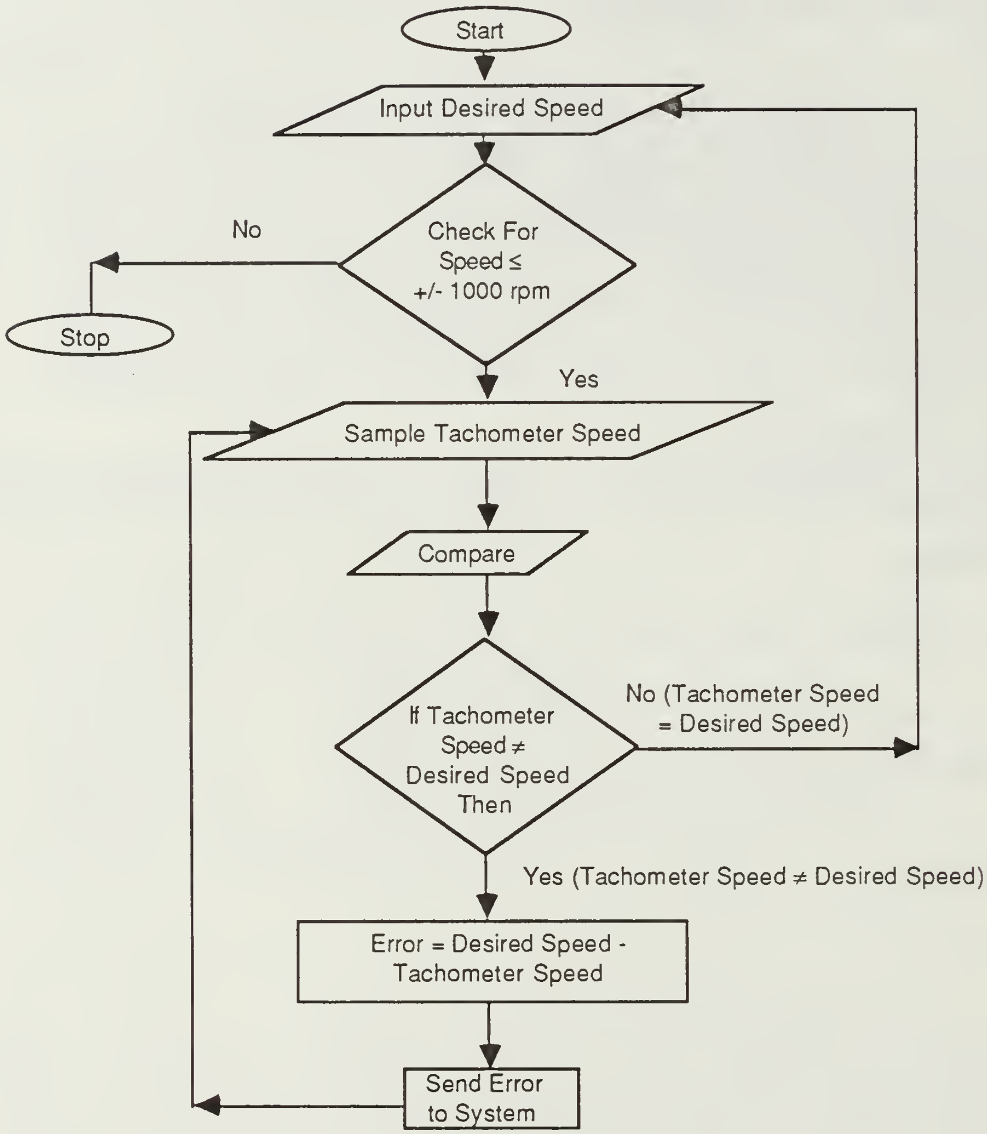

Figure A6. Flow chart for closed loop control with the micro in the loop.

APPENDIX D

MAC/MACADIOS OPERATION

1. HARDWARE

The actual computer used was a Macintosh (Mac) 512K. Near the completion of the work the computer was upgraded to the Macintosh 512K Enhanced. The computer has 512K of memory (RAM), 128K ROM and an internal 800K double sided disk drive, along with the standard keyboard and mouse. An external 800K double-sided disk drive was used for additional data storage.

The corresponding analog-to-digital convertor for the Mac is a product from GW Instruments called MacADIOS. It comes with its own software and serial interface to the Mac. It has 4 analog outputs, 8 analog inputs, 16 digital outputs, 16 digital inputs, a programmable clock signal and a programmable counter (can be used as a timer). The MacADIOS uses MicroSoft BASIC or C as a programming language. All input/output signals are available at the connectors on the front panel of the MacADIOS through standard banana, BNC and two 37 pin "D-series" connectors.

2. SOFTWARE

The software supplied with the MacADIOS consists of the 5 Instruments Package, MacADIOS Manager, XY MaCorder, Microsoft BASIC library calls and source code for Manx Aztec C, as well as calibration and hardware test programs and example BASIC programs. The 5 Instruments software allows the Mac/MacADIOS system to emulate an oscilloscope, spectrum analyzer, sonogram, spectrogram and 8 input digital voltmeter. The MacADIOS Manager (MM) is a general purpose data acquisition program that allows up to four different waveforms to be viewed and compared on one graph called the View 4

Window. The graphics editor portion of the MM allows waveforms to be edited in a graphical format which is particularly useful in preparing waveforms to be used for output. The Experiment Editor Window allows for the development of programs which will send waves out of the MacADIOS as well as record incoming data and visually present what is going on. The programming format is the same as that of BASIC. The last major window of the MM is the Monitor Window. The Monitor Window allows the Mac/MacADIOS system to emulate an 8 channel digital voltmeter as well as allow sending voltages through 4 of the analog output channels or all 16 digital channels.

3. OPERATION

The MacADIOS is connected to the Mac via the modem port. An adapter is provided for the MacPlus if used. A system disk was made consisting of the latest system folder with the text editor MOCKWRITE as a desk accessory, and minimum system fonts installed. Then the MacADIOS Manger (MM) application, MacADIOS CALLS file, and MicroSoft BASIC (binary) application were copied onto the disk . This allows sufficient room on an 800K disk to create programs and manipulate data with a minimum of disk swapping.

Initial work was done in the MM. This program is opened with standard Mac procedures and the Monitor Window selected from under the Window menu. Selecting the channel(s) and specifying the output in millivolts initializes the software to send the corresponding data out of the selected channels. Point and click on the start button and the desired signal is sent and will continue to be sent until stop is clicked, a new value is assigned and the start button clicked. The MM keeps the same voltage at the output channel until specifically changed or the MacADIOS is turned off. Due to the high input impedance of the MacADIOS, the input channels that do not have any input attached to them will indicate random values.

This set-up is useful when experimenting with the lab set-up when desired millivolt signals are needed to be sent to the system or observed. If a specific sequence of events are needed to be recorded or sent to the system, then either the Experiment Window should be used or a program written in BASIC. Using BASIC provides more flexibility and was used for the final part of this work. The instruction manual for the MacADIOS provides samples of programs written in BASIC and all library calls. All that is required in the BASIC program is to call the library of BASIC calls that comes with the MacADIOS, initialize the modem port for the MacADIOS and then execute the code for the sequence of events to occur. This may involve sampling from a particular channel, sending a signal to an output channel, or manipulating the data recorded for further processing.

There are many methods available within the MM to manipulate data. Many of the functions available from BASIC are available from within the Experiment window. Waveforms (data) recorded from the experiments run from within the MM may be saved and later reopened in BASIC. However this data is saved in binary format and must first be converted into a format readable by BASIC. A sample program to do this is given in the MacADIOS manual.

APPENDIX E

MAC/MACADIOS PROBLEMS

As the Mac/MacADIOS system was being set-up to run, several problems were encountered. First was the problem of conditioning the signal from the tachometer. There was noise, not only from the tachometer, but in the unshielded wires being used throughout the set-up. The problem became apparent when performing simple voltage recording tests. Sampling the output of the tachometer, it was observed that the analog signal displayed in the Monitor Window of the MacADIOS Manager software, would not steady out to a constant value. The least significant two or three digits continuously oscillated. To correct this, as well as the fact that the maximum input allowed into the MacADIOS was ten volts, a signal conditioner was inserted into the output of the tachometer prior to the MacADIOS. The signal conditioner consisted of a voltage divider and a capacitor matched to bring the noise level as seen in the Monitor Window to a minimum. With the signal conditioner installed the oscillation was greatly reduced.

Next a problem occurred with the noise level changing from time to time. The cause was determined to be related to the use of different grounds between the equipment in use. This was resolved by ensuring all equipment was connected to the same outlet for power and connecting all system grounds to a common ground. Additionally, to avoid picking-up noise from other operating equipment, all interfacing cables used were converted to shielded coaxial, where possible.

A precautionary step worth noting, is that when programming the user interface it is important to keep in mind the maximum allowed current through the servovalve. The algorithm should provide the protection for the servovalve by limiting the output voltage of the DAC to a level that does not exceed the limit of the servovalve. Although the limiter

circuitry of the servoamplifier will still be in effect, programs should provide the initial protection. As such, some preset limits on maximum range of speed in order to provide maximum sensitivity and protection needed to be defined. For this work +/- 1000 rpm was used. This corresponds to a feedback of 45 volts stepped down to a maximum of 4.5 volts by the voltage divider network and a maximum output voltage of the DAC of 4 volts.

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